Patent Application of

Wil McCarthy and Gary E. Snyder

for

QUANTUM DOT FIBER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is entitled to the benefit of Provisional Patent Application Ser.#60/312264, filed 13 August 2001.

BACKGROUND – FIELD OF INVENTION

This invention relates to a fiber whose exterior surface has quantum dots attached to it. The invention has particular but not exclusive application in materials science, as a programmable dopant which can be placed inside bulk materials and controlled by external signals.

BACKGROUND – DEFINITIONS AND THEORY OF OPERATION

The fabrication of very small structures to exploit the quantum mechanical behavior of charge carriers (e.g., electrons or electron "holes") is well established. Quantum confinement of a carrier can be accomplished by a structure whose linear dimension is less than the quantum mechanical wavelength of the carrier. Confinement

in a single dimension produces a "quantum well," and confinement in two dimensions produces a "quantum wire."

A quantum dot (QD) is a structure capable of confining carriers in all three dimensions. Quantum dots can be formed as particles, with a dimension in all three directions of less than the de Broglie wavelength of a charge carrier. Such particles may be composed of semiconductor materials (including Si, GaAs, InGaAs, InAlAs, InAs, and other materials), or of metals, and may or may not possess an insulative coating. Such particles are referred to in this document as "quantum dot particles." A quantum dot can also be formed inside a semiconductor substrate, through electrostatic confinement of the charge carriers. This is accomplished through the use of microelectronic devices of various design (e.g., a nearly enclosed gate electrode formed on top of a P-N-P junction). Here, the term "micro" means "very small" and usually expresses a dimension less than the order of microns (thousandths of a millimeter). The term "quantum dot device" refers to any apparatus capable of generating a quantum dot in this manner. The generic term "quantum dot," abbreviated QD in certain drawings, refers to any quantum dot particle or quantum dot device.

Quantum dots can have a greatly modified electronic structure from the corresponding bulk material, and can serve as dopants. Because of their unique properties, quantum dots are used in a variety of electronic, optical, and electro-optical devices.

Kastner (1993) points out that the quantum dot can be thought of as an "artificial atom," since the carriers confined in it behave similarly in many ways to electrons confined by an atomic nucleus. The term "artificial atom" is now in common use, and is often used interchangeably with "quantum dot." However, for the purposes of this document, "artificial atom" refers specifically to the pattern of confined carriers (e.g., an electron gas), and not to the particle or device in which the carriers are confined.

The term "quantum dot fiber" refers to a wire or fiber with quantum dots attached to, embedded in, or forming its outer surface. This should not be confused with a quantum wire, which is a structure for carrier confinement in two dimensions only.

BACKGROUND – DESCRIPTION OF PRIOR ART

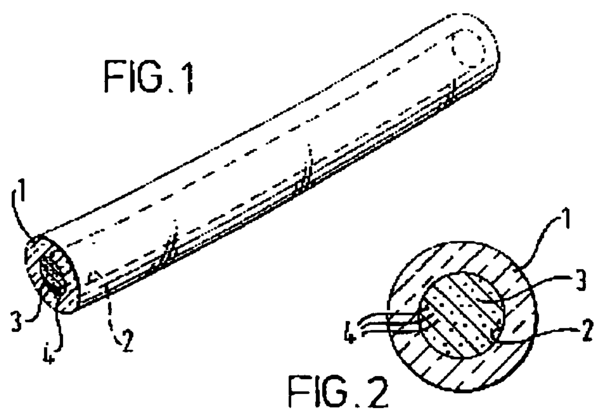
Quantum dots are currently used as near-monochromatic fluorescent light sources, laser light sources, light detectors (including infra-red detectors), and highly miniaturized transistors, including single-electron transistors. They can also serve as a useful laboratory for exploring the quantum mechanical behavior of confined carriers. Many researchers are exploring the use of quantum dots in artificial materials, and as programmable dopants to affect the optical and electrical properties of semiconductor materials.

Kastner (1993) describes the future potential for "artificial molecules" and "artificial solids" composed of quantum dot particles. Specifics on the design and functioning of these molecules and solids are not provided. Leatherdale et. al. (2000) describe, in detail, the fabrication of "two- and three-dimensional... artificial solids with potentially tunable optical and electrical properties." These solids are composed of colloidal semiconductor nanocrystals desposited on a semiconductor substrate. The result is an ordered, glassy film composed of quantum dot particles, which can be optically stimulated by external light sources, or electrically stimulated by attached electrodes, to alter its optical and electrical properties. However, these films are extremely fragile, and are "three dimensional" only in the sense that they have been made up to several microns thick. In addition, the only parameter which can be adjusted electrically is the average number of electrons in the quantum dots. Slight variations in the size and composition of the quantum dot particles mean that the number of electrons will vary slightly between dots. However, on average the quantum dot particles will all behave similarly.

The embedding of metal and semiconductor nanoparticles inside bulk materials (e.g., the lead particles in leaded crystal) is also well established. These nanoparticles are quantum dots whose characteristics are determined by their size and composition, and they serve as dopants for the material in which they are embedded, to alter selected optical or electrical properties. However, there is no means or pathway by which these quantum dot particles can be stimulated electrically. Thus, the doping characteristics of the quantum dots are fixed at the time of manufacture.

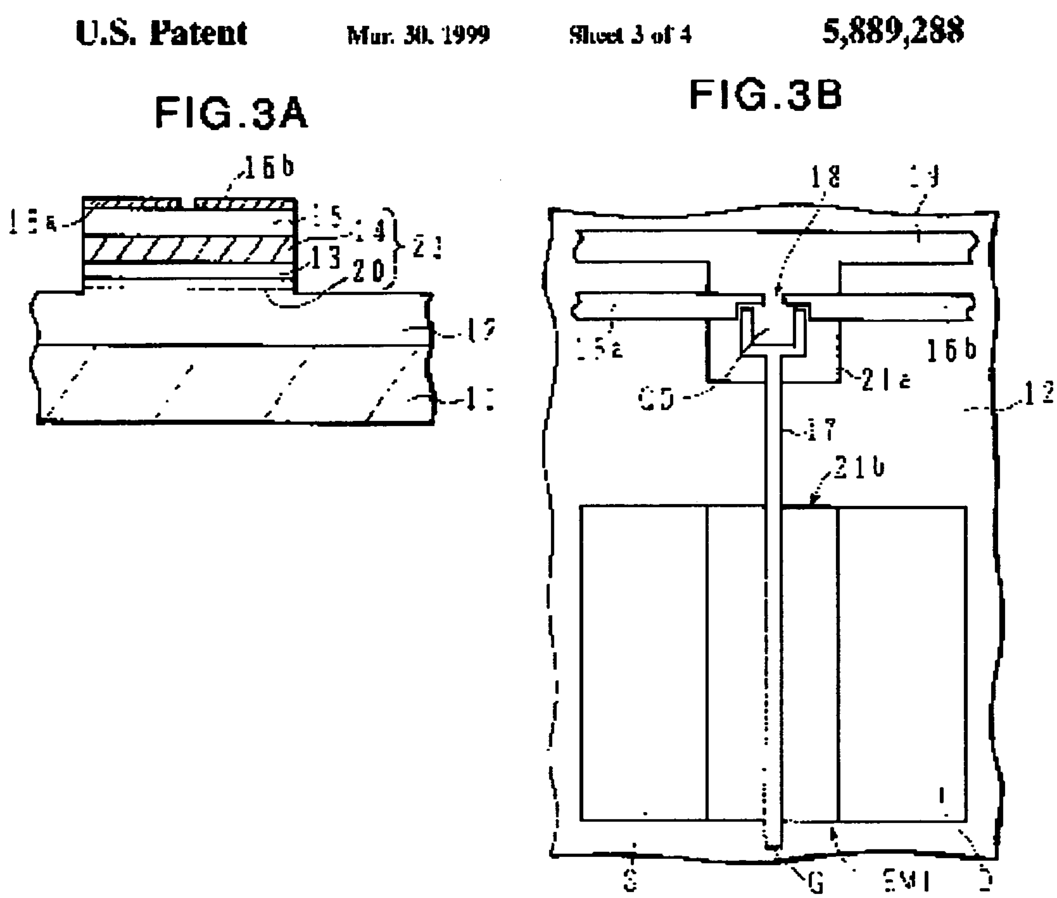
However, the prior art almost completely overlooks the broader materials-science implications of quantum dots. The ability to place programmable dopants in a variety of materials implies a useful control over the bulk properties of these materials. This control could take place not only at the time of fabrication, but also at the time of use, in response to changing needs and conditions. However, there is virtually no prior art discussing the use, placement, or control of quantum dots in the interior of bulk materials. Simiarly, there is no prior art discussing the placement of quantum dots on the outside of an electrically or optically conductive fiber. There are hints of these concepts in a handful of references, discussed below:

U.S. Patent Mar. 9, 1999 **5,881,200**



U.S. patent 5,881,200 to Burt (1999) discloses an optical fiber (1) containing a central opening (2) filled with a colloidal solution (3) of quantum dots (4) in a support medium. The purpose of the quantum dots is to produce light when optically stimulated, for example to produce optical amplification or laser radiation. The quantum dots take

the place of erbium atoms, which can produce optical amplifiers when used as dopants in an optical fiber. This fiber could be embedded inside bulk materials, but could not alter their properties since the quantum-dot dopants are enclosed inside the fiber. In addition, no means is described for exciting the quantum dots electrically. Thus the characteristics of the quantum dots are not programmable, except in the sense that their size and composition can be selected at the time of manufacture.



U.S. patent 5,889,288 to Futasugi (1999) discloses a semiconductor quantum dot device which uses electrostatic repulsion to confine electrons. This device consists of electrodes (16a, 16b, and 17) controlled by a field effect transistor, both formed on the surface of a quantum well on a semi-insulating substrate (11). This arrangement permits the exact number of electrons trapped in the quantum dot (QD) to be controlled, simply by varying the voltage on the gate electrode (G). This is useful, in that it allows the

"artificial atom" contained in the quantum dot to take on characteristics similar to any natural atom on the periodic table, including transuranic and asymmetric atoms which cannot easily be created by other means. Unfortunately, the two-dimensional nature of the electrodes means that the quantum dot can exist only at or near the surface of the wafer, and cannot serve as a dopant to affect the wafer's interior properties.

Turton (1995) describes the possibility of placing such quantum dot devices in two-dimensional arrays on a semiconductor microchip. This practice has since become routine, although the spacing of the quantum dot devices is typically large enough that the artificial atoms formed on the chip do not interact significantly. Such a chip also suffers from the limitation cited in the previous paragraph: its two-dimensional structure prevents its being used as a dopant except near the surface of a material or material layer.

Goldhaber-Gordon et. al (1997) describe what may be the smallest possible single-electron transistor. This consists of a "wire" made of conductive C_6 (benzene) molecules, with a "resonant tunneling device" inline which consists of a benzene molecule surrounded by CH_2 molecules which serve as insulators. The device is described (incorrectly, I believe) as a quantum well rather than a quantum dot, and is intended as a switching device (transistor) rather than a confinement mechanism for charge carriers. However, in principle the device should be capable of containing a small number of excess electrons and thus forming a primitive sort of artificial atom.

McCarthy (1999), in a science fiction story, includes a fanciful description of "wellstone," a form of "programmable matter" made from "a diffuse lattice of crystalline silicon, superfine threads much finer than a human hair," which use "a careful balancing of electrical charges" to confine electrons in free space, adjacent to the threads. This is probably physically impossible, as it would appear to violate Coulomb's Law, although I do not wish to be bound by this. Similar text by the same author -- myself -- appears in McCarthy (August 2000) and McCarthy (05 October 2000). Detailed information about the composition, construction, or functioning of these devices is not given.

The first detailed and technically rigorous discussion of a quantum dot fiber occurs in Provisional Patent Application Ser.#60/312264, filed 13 August 2001 by myself. The Provisional Patent Application forms the basis of this patent application.

SUMMARY

In accordance with the present invention, a quantum dot fiber comprises a fiber containing one or more control wires, which control quantum dots on the exterior surface of the fiber.

OBJECTS AND ADVANTAGES

Accordingly, several objects and advantages of the present invention are:

(a) that it provides a three-dimensional structure for quantum dots which can be considerably more robust than a nanoparticle film. For example, a contiguous glass fiber or metal wire is held together by atomic bonds, as opposed to the much weaker Van der Waals forces which hold nanoparticle films together.

(b) that it provides a method for the electrical and/or optical stimulation of quantum dot particles embedded inside bulk materials. The fiber can consist of, or include, one or more metal wires or optical conduits which are electrically and/or optically isolated from the material in which they are embedded. These pathways can branch directly to the surfaces or interiors of the quantum dot particles, providing the means to stimulate them.

(c) that is provides a method for embedding and controlling electrostatic quantum dot devices (and potentially other types of quantum dot devices) inside bulk materials, rather than at their surfaces.

(d) that it permits the doping characteristics of quantum dots inside a material to be controlled by external signals, and thus varied by a user at the time of use. Thus, the properties of the bulk material can be tuned in real time, in response to changing needs or circumstances.

(e) that the quantum dot fiber can be used outside of bulk materials, in applications where quantum dots, quantum wires, and nanoparticle films are presently used. For example, the quantum dot fiber can serve as a microscopic light source or laser light source which is both long and flexible.

(f) that multiple quantum dot fibers can be arranged on a surface to produce two-dimensional materials analogous to nanoparticle films, but much stronger.

(g) that multiple quantum dot fibers can be woven, braided, or otherwise arranged into three-dimensional structures whose properties can be adjusted through external signals, forming a type of "programmable matter" which is a bulk solid with electrical and optical properties (and potentially other properties such as magnetic, mechanical, and chemical properties) that can be tuned in real time through the adjustment of artificial atoms.

(h) that the resulting programmable materials, unlike nanoparticle films, can contain artificial atoms of numerous and wildly different types, if desired. Thus, the number of potential uses for the quantum dot fiber materials is vastly greater than for the materials based on nanoparticle films.

DRAWING FIGURES

In the drawings, closely related figures have the same number but different alphabetic suffixes, except for figures 1 and 2 from the prior art, which are closely related.

Figs 1 and 2 are from the prior art, U.S. patent 5,881,200 to Burt (1999), showing an optical fiber containing a central opening filled with a colloidal solution of quantum dots in a support medium.

Figs 3a and 3b are from the prior art, U.S. patent 5,889,288 to Futasugi (1999), showing a semiconductor quantum dot device which uses electrostatic repulsion to confine electrons.

Figs 4a and 4b are from the present invention, in its preferred embodiment. This is a multilayered microscopic fiber which includes a quantum well, surface electrodes which form quantum dot devices, and control wires to carry electrical signals to the electrodes.

Figs 5a and 5b disclose an additional embodiment of the present invention, in which the quantum dot devices (quantum well and electrodes) on the fiber's surface are replaced with quantum dot particles.

Figs 6a and 6b disclose a variant of this embodiment, in which the fiber comprises a single control wire with quantum dot particles attached to its exterior surface.

Figs 7a and 7b disclose still another alternative embodiment of the present invention, comprising an ordered chain of quantum dot particles alternating with control wire segments.

REFERENCE NUMERALS IN DRAWINGS

Reference numerals for the prior art are not included here. The reference numerals for the present invention are as follows:

(30) Surface electrodes

(31) Positive layers of quantum well

(32) Negative layer of quantum well

(33) Memory layer, comprising microscopic transistors to switch electrodes on and off. This layer is optional, since this switching can be accomplished external to the fiber.

(34) Control wires

(35) Insulator

(36) Control wire branches to fiber surface

(37) Quantum dot particles

(38) Control wire segments

(QD) Quantum dot region

Please note that Figures 1-3 are from the prior art, and are included for reference in the Prior Art section of this specification. To prevent confusion, the figures for the present invention, in the drawing pages below, are numbered 4 and above.

DESCRIPTION -- FIGS. 4a and 4b -- PREFERRED EMBODIMENT

Figures 4a (isometric view) and 4b (end view) show a preferred embodiment of the invention, which is a fiber containing control wires (34) in an insulating medium (35), surrounded by layers of semiconductor or other materials (31) and (32) which form a quantum well, plus an optional memory layer (33). The central layer (32) of the quantum well must be smaller in thickness than the de Broglie wavelength of the charge carriers to be confined in it. For an electron at room temperature, this would be approximately 20

nanometers. Thicker quantum wells are possible, although they will only operate at temperatures colder than room temperature. Thinner quantum wells will operate at room temperature, and at higher temperatures so long as the de Broglie wavelength of the carriers does not exceed the thickness of the confinement layer (32).

The surface of the fiber includes conductors which serve as the electrodes (30) of a quantum dot device, which confine charge carriers in the quantum well into a small space or quantum dot (QD), forming an artificial atom. The electrodes (30) are powered by control wire branches (36) reaching from the control wires (34) to the fiber's surface. The control wires and control wire branches would normally be electrical conductors, although in principle they could be made of other materials, such as semiconductors or superconductors.

The memory layer (33) comprises microscopic transistors which serve as switches, and which are capable of turning voltages to the surface electrodes (30) on and off. This layer is optional, since this switching can be accomplished external to the fiber. However, it is included here for clarity.

Note that the exact arrangement of the various layers can be slightly different than is depicted here, without altering the essential functioning of the quantum dot fiber. For example, the cross-section may be any oval or polygon shape, and the inslulated control wires need not be located at the fiber's center, although that seems to be the most convenient place to locate them.

FIGS 5a-7b – ADDITIONAL EMBODIMENTS

Figures 5a (isometric view) and 5b (end view) show an additional embodiment, in which control wire segments (38) alternate with quantum dot particles (37). The dimensions of both the wire segments and the quantum dot particles, while generally microscopic, could cover a broad range of values while retaining useful properties for the quantum dot fiber.

Figures 6a (isometric view) and 6b (end view) show another additional embodiment, in which quantum dot particles (37) are attached to the surface of a non-insulated control wire (34). In general, this wire would be an electrical conductor, semiconductor, or superconductor, but could in principle be another type of conduits for carrying energy to stimulate the quantum dot particles. Dimensions can once again cover a broad range of microscopic values.

Figures 7a (isometric view) and 6b (end view) show still another additional embodiment, in which the fiber comprises multiple control wires (34) surrounded by insulation (35), with control wire branches (36) leading to quantum dot particles (37) on the surface of the fiber. For clarity, an optional memory layer (33) is included as well. In this embodiment, the control wires could be conductors, semiconductors, or superconductors, but could also be optical fibers, or other types of conduits for carrying energy to stimulate the quantum dot particles (37). Again, the dimensions can cover a broad range of microscopic values while retaining useful optical, electrical, and other properties for the quantum dot fiber.

ALTERNATIVE EMBODIMENTS

There are various possibilities for making the quantum dot fiber of different materials, and in different configurations. The most advantageous configurations are the smallest, since smaller quantum dots can contain charge carriers at higher energies and thus display atom-like behavior at higher temperatures. The smallest conceivable quantum dot fiber would be similar in design to the single-electron transistor described in Goldhaber-Gordon et. al (1997), although molecules the size of benzene rings or smaller, if employed as quantum dot particles, will be unable to hold large numbers of excess charge carriers. This limits their usefulness in generating artificial atoms. A somewhat larger but more practical design is to employ electrically conductive nanotubes, such as a carbon nanotubes, as the control wire segments (38), and fullerene-type molecules, such as carbon fullerenes, as the quantum dot particles (37).

ADVANTAGES

From the description above, our quantum dot fiber can be seen to provide a number of cabailities which are not possible with the prior art:

(a) The ability to place programmable dopants in the interior of bulk materials.

(b) The ability to control the properties of these dopants in real time, through external signals. In contrast, the properties of dopants based solely on quantum dot particles can only be controlled at the time of manufacture.

(c) The ability to form programmable materials containing "artificial atoms" of diverse types. In contrast, programmable materials based on nanoparticle films can contain only multiple instances of one "artificial element" at a time.

Also from the above description, several advantages over the prior art become evident:

(d) Materials based on quantum dot fibers will, in general, be much stronger than materials based on nanoparticle films.

(e) Quantum dot fibers can be used in numerous applications where quantum dots and quantum wires are presently employed. However, the quantum dot fiber provides isolated energy channels for the optical or electrical stimulation of the quantum dots, permitting the dots to be excited without also affecting the surrounding medium or materials. For example, light can be passed through a quantum dot by means of the fiber, without also being shined on or through surrounding areas. Similarly, an electrical voltage can be channeled to a quantum dot without passing through the surrounding medium. Thus, quentum dot fibers can be used in numerous applications where quantum dot devices or particles would prove disruptive.

OPERATION -- FIGS 4a and 4b

The preferred manner of using the quantum dot fiber is to place a fiber or a plurality of fibers, as needed, inside a bulk material (e.g., a semiconductor), or to weave or braid them together into a two-or three-dimensional structure. Material layers (31) and (32) form a quantum well, which traps charge carriers in a quantum (wavelike) manner in the central layer (32).

Voltages (or other energy if appropriate) are then passed through the control wires (30) from an external source. These voltages pass from the control wires to the control wire branches (36), where they are carried to electrodes (30) on the sufrace of the fiber. Alternatively, the control wire branches may pass through an optional memory layer (33) which consists of transistors or other switches which are capable of switching the voltage pathways open or closed. From the memory layer, the control wire branches would then lead to the electrodes at the surface of the fiber. Once the voltage reaches the electrodes, it creates an electrostatic repulsion which affects the carriers trapped in the quantum well, herding them into small areas known as quantum dots, where they form artificial atoms.

Adjustment of the voltages on the electrodes can then affect the characteristics of the artificial atoms, including:

(a) size

(b) shape or symmetry

(c) number of charge carriers

(d) energy levels of the carriers

The resulting changes in the artificial atom can dramatically affect its properties as a dopant.

Depending on the number of control wires inside the fiber and the number of quantum dot devices along its surface, the artificial atoms located near the fiber's surface

(in the confinement layer 32) may all be identical, may represent multiple "artificial elements" in regular or irregular sequences, or may all be different.

OPERATION -- FIGS 5a and 5b

The operation of this embodiment is very similar to the previous one, with the exception that the carriers are confined in quantum dot particles (37) rather than by electrostatic repulsion and a quantum well. Voltages (or optical energy or other energy) are passed through the control wires (34) from an external source, and brought to the fiber's surface via control wire branches (36). These voltages are then carried to the quantum dot particles, in order to stimulate them. This stimulation can then affect the properties of the artificial atoms contained in the quantum dot particles, including:

(a) number of carriers

(b) energy levels of the carriers

As before, the resulting changes in the artificial atom can dramatically affect its properties as a dopant.

Depending on the number of control wires inside the fiber and the number of quantum dot particles along its surface, the artificial atoms located in the quantum dot particles may all be identical, may represent multiple "artificial elements" in regular or irregular sequences, or may all be different.

OPERATION -- FIGS 6a and 6b

The operation of this embodiment is similar to the previous one, with the exception that the fiber comprises a single control wire (34), with quantum dot particles (37) attached to its outer surface. The quantum dots are stimulated by voltage (or optical energy or other energy) passing through the control wire. This stimulation can then affect the properties of the artificial atoms contained in the quantum dot particles, including:

(a) number of carriers

(b) energy levels of the carriers

As before, the resulting changes in the artificial atom can dramatically affect its properties as a dopant.

The capabilities of this embodiment are more limited, in that (barring minor variations in the size and composition of the quantum dot particles) all the artificial atoms along the fiber will have the same characteristics. In some cases it may be necessary to place a high impedance in series with the fiber's control wire in order for a voltage to drive charge carriers into the quantum dots.

OPERATION -- FIGS 7a and 7b

The operation of this embodiment is similar to the previous one, with the exception that the quantum dot particles (37) are not attached to the surface of the fiber, but are an integral part of its structure, alternating with control wire segments (38). A voltage (or optical energy or other energy) is passed through the control wire, and passes directly into and through the quantum dot particles, stimulating them. This stimulation can then affect the properties of the artificial atoms contained in the quantum dot particles, including:

(a) number of carriers

(b) energy levels of the carriers

As before, the resulting changes in the artificial atom can dramatically affect its properties as a dopant.

The capabilities of this embodiment are even more limited than the previous one, in that resistive losses across each quantum dot particle will cause the voltage to drop significantly across each segment of the fiber. Thus, each successive artificial atom along the fiber's length will have a lower voltage (or illumination or other excitation) than the one before it. Thus, the artificial atoms cannot be individually controlled and will not be identical. Instead, the user may select a sequence of artificial elements, of successively lower energies, to be presented by the fiber.

CONCLUSION, RAMIFICATIONS, AND SCOPE

Accordingly, the reader will see that the quantum dot fiber of this invention can be used as a programmable dopant inside bulk materials, as a building block for new materials with unique properties, and as a substitute for quantum dots and quantum wires in various applications (e.g., as a light source or laser light source).

Although the description above contains many specificities, these should not be construed as limiting the scope of the invention but merely providing illustrations of some of the presently preferred embodiments of this invention. For example, the fiber could have non-circular shapes in cross-section, including a flat ribbon with quantum dots on one or both sides; the "artificial atoms" could be composed of charge carriers other than electrons, the control wires could be replaced with semiconductor, superconductor, optical fiber, or other conduits for carrying energy; the control wires could be antennas for receiving signals and energy from electromagnetic waves; any of the embodiments listed here could be replicated on a molecular scale through the use of specialized molecules such as carbon nanotube wires and fullerene quantum dot particles; the quantum dots could be other sorts of particles or devices than those discussed herein; the number and relative sizes of the quantum dots with respect to the fiber could be significantly different than is shown in the drawings.

Thus the scope of the invention should be determined by the appended claims and their legal equivalents, rather than by the examples given.